Best Practices Guide:

Macroeconomic Modeling for Climate Change Planning

Prepared for:
Energy and Environment Training Program
Office of Energy, Environment and Technology
Global Bureau, Center for Environment
United States Agency for International Development

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Office of Energy, Environment & Technology
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Washington, DC 20523-1810

May 2002

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List of Acronyms

AEEI	autonomous energy efficiency improvement
CES	constant elasticity of substitution
CGE	computable general equilibrium models
CO_2	carbon dioxide
dLA	deLucia and Associates, Inc.
EV	equivalent variation measure of welfare
GAMS	Generalized Algebraic Modeling System
GDP	gross domestic product
GHG	greenhouse gases
GHJ	Garbaccio, Ho and Jorgenson
IAMs	Integrated Assessment Models
IIE	Institute of International Education
IO	input-output
IPCC	Intergovernmental Panel on Climate Change
SAM	social accounting matrix
SGM	Second Generation Model
USAID	United States Agency for International Development
UNDP	United Nations Development Programme

Acknowledgments

USAID's Office of Energy, Environment and Technology (EET), would like to thank the team of dedicated individuals who wrote, reviewed and produced the *Best Practices Guide: Macroeconomic Modeling for Climate Change Planning.* EET would also like to recognize the Energy and Environment Training Program Team Leader, Mark Murray and Deputy Team Leader, Nohemi Zerbi for their guidance in the Energy and Environmental Training Program under which this Guide was produced.

The material found in this Guide has been adapted from a three-week training course held in Boston, Massachusetts, by an international team of instructors led by Christian Dufournaud of the University of Waterloo in Toronto, Canada. Other instructors included Stephen S. Bernow of Tellus Institute, Mun S. Ho of the Kennedy School of Government at Harvard University, Amit Kanudia of McGill University, Ronald D. Sands of Pacific Northwest National Laboratory (PNNL) and P.R. Shukla of the Indian Institute of Management, Ahmedabad, India.

These seminars were presented to a multinational audience, members of which represented the countries of Bangladesh, Ghana, Kazakhstan, Mexico, the Philippines and Romania. EET would like to acknowledge the expertise and commitment of the principal coordinator of the course and author of this Guide, Michael Lesser of deLucia and Associates, Inc., as well as all those who contributed to the development of materials for the seminar and this guide. Their commitment to providing the highest quality training materials has allowed this Guide to be of equally high quality. EET would also like to thank the Institute of International Education for their support in bringing this Guide to completion, as well as their commitment to implementing and administering quality training programs.

Introduction

The United States Agency for International Development's (USAID) Global Center for Environment sponsored a series of courses designed to develop technical leadership capacity in energy development and greenhouse gas emissions reduction that is both friendly to the environment and beneficial to economic growth. Through a contract with the Energy Group of the Institute of International Education (IIE), deLucia and Associates developed the *Best Practices Guide: Macroeconomic Modeling for Climate Planning*. This guide is for government analysts and decision-makers and others involved in macroeconomic and climate planning analysis. It discusses methodological issues and case studies related to the macroeconomic impacts of climate change policies.

IIE's Energy Group provides assistance and training to government and business leaders to develop the skills and knowledge they will need to succeed in meeting their energy management and national development goals.

deLucia and Associates, Inc. (dLA) is a private, independent consulting firm with extensive experience in energy, environment and infrastructure issues, covering all aspects of policy analysis and project development. The firm specializes in the issues and problems of the developing countries, and dLA has worked in nearly 40 countries during the past 16 years, primarily for multi-/bi-lateral development agencies. This work has covered financial and economic analyses of conventional, renewable and traditional energy sources as well as energy use and related environmental impacts. dLA currently focuses on sustainable projects that focus on poverty alleviation; this work includes project development and financing with an emphasis on small-scale infrastructure provision.

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MACROECONOMIC MODELING FOR CLIMATE PLANNING

Sound national economic policy necessarily addresses elements of change in society to ensure sustained economic growth and a comfortable or improved standard of living for its citizens. One such element, which is causing increasing concern in the international community today, is global climate change. The warming trend in the Earth's mean surface temperature, resulting from increased concentrations of greenhouse gas (GHG) emissions in the atmosphere, stems primarily from human activities associated growing urbanization and industrialization worldwide. The potential impact of global warming could have devastating affects on national economies, through its impact on natural resource distribution, human health and severe weather events. Developing countries are particularly vulnerable to the impacts of climate change, having limited resources available to manage them, and are particularly sensitive to the costs of climate change mitigation policies given their need to raise their standards of living.

Fortunately, there are some policies that can both promote economic growth and protect the global community against the economic consequences of climate change. When such "win-win" policies alone are insufficient to achieve national GHG emission reduction targets, the challenge becomes identifying policies that encourage the least cost means of reducing GHG emissions and they still continue to mitigate the impact of global warming. Identifying the "win-win" and least cost policies on a national level requires both micro- and macro-economic analyses. The objective of this report is to introduce policy makers and analysts to the macroeconomic consequences of GHG mitigation policies and how they can be modeled.

The report is in three parts. First, we discuss the linkages between national economic growth and climate change planning. We then present the general types of macroeconomic models available for use in climate planning at the national level. Finally, we examine case studies of how macroeconomic modeling of climate change policies has been undertaken.

PART I: LINKAGES BETWEEN NATIONAL ECONOMY AND CLIMATE CHANGE

A. Sources and Sinks of GHG Emissions and Vulnerabilities

The mitigation of GHG is a problem that is best addressed from both the short and long-term perspective. There are several types of economic-energy models useful to assess the macroeconomic consequences of policy choices for GHG mitigation. The purpose of the models is to provide policy makers with a new perspective on how to improve policy formulation in this area of global concern.

One place to start is to briefly define the sources of GHG emissions and the possible sinks. It is well established that most GHG emissions are anthropogenic in origin, although some are naturally occurring. Since it is the actions of human beings that cause most GHG emissions, the actions of human beings must be addressed in finding policy solution to reduce them.

Research indicates most GHG emissions result from energy generation and the production of goods and services. Household production and consumption are secondary, though not negligible, sources for GHG emissions. The magnitude of the problem is easy to understand when we consider that all aspects of human activity contribute to GHG emissions. On the other hand, it is also generally agreed that the natural environment can sustain certain levels of GHG emissions. The most ubiquitous molecule that contributes to GHG emissions is carbon dioxide (CO_2)[1], and it accounts for more than half of the increase in global warming from anthropogenic GHG emissions. The environment has several carbon sinks, or natural mechanisms for absorbing CO_2. The turnover of the oceans to absorb heat in the environment and the fixing of carbon by trees are two of these natural sinks.

Unfortunately, the ability of trees to fix carbon is limited to their growing period and there is considerably more deforestation occurring than planting. Also, it is doubtful that carbon fixation by trees and absorption by the oceans can offset the huge increase in GHG emissions that are anticipated to accompany aggressive economic development plans of most of the world's developing nations. Some studies suggest that heat absorption by oceans and eventual turnover can take 1000 years (Nordhaus, 1994). Consequently, GHG mitigation hinges on human action, particularly policy reform, which consciously reduces emissions. The macroeconomic impacts of policies for GHG mitigation are the focus of this report.

B. Types of Benefits and Costs

The cost-benefit analysis framework can provide insights into policy questions that arise in GHG mitigation. Just as national economies differ in their vulnerability and contributions to global warming, so do the efficacy, costs, and the resulting macroeconomic impacts of their policies. These impacts of GHG emissions constitute an externality in the classic sense and hence are a worldwide concern. There is also the issue that the benefits and costs of reducing emissions do not occur at the same time; in fact, the costs are often short-term, while the benefits are long-term. Given these conditions, one of the central issues in how to address the global warming problem is the request to emerging economies to reduce their GHG emissions now, possibly at the expense of economic growth now and possibly in the future as well. In analyzing and negotiating the potential options for managing the problem of climate change, the different perspectives of countries at different stages of development are being raised and will need to be addressed.

From the point of view of macroeconomic analysis of climate planning, there are two perspectives. The very long-term perspective (e.g. greater than 50 years) concerns the overall picture of the positive net benefits of mitigating GHG emissions by successfully meeting national emission level targets. From this perspective, the primary benefits are the avoided costs arising from the environmental consequences of global warming (e.g. negative impacts on agriculture, coastal areas and public health). Then there is the second perspective, which involves the short to long-term need for evaluating the economic impacts of various GHG mitigation policies necessary to avoid these longer-term costs. This second perspective can be viewed as an analysis of the benefits and costs of reduced emissions, with the goal of minimizing the net costs of meeting certain emission levels (thus maximizing the net benefits over the longer period). This report focuses on this second cost-benefit analysis and presumes that the very long-term analysis demonstrates the need for GHG mitigation policies.

The nature of GHG mitigation costs and benefits can be articulated in the general terms, for example, that governments will maximize the present value of "welfare" summed over the entire set of its citizens. Welfare is defined more specifically as the difference between benefits and costs in present value, wherein benefits and costs are defined in monetary terms. In GHG mitigation, net benefits are usually measured in terms of GDP per capita. Costs are seen as investments required and opportunities foregone

[1] Other GHGs include methane, nitrous oxide, and various carbon compounds with chlorine and/or fluorine. GHGs have different relative impacts on global warming (i.e. global warming potential), and these relative impacts also change over time. Commonly, the carbon equivalents of non-CO_2 GHGs are based on their 100-year global warming potentials, i.e. methane = 21.

as a result of implementation of specific GHG mitigation policies. Though GDP per capita is the primary measure for macroeconomic impact modeling, there are other impacts that are examined, such as impacts on various household income groups, consumers versus businesses, intertemporal differences, and regional/local environmental impacts.

Governments use the GDP per capita criterion because "more" for all citizens is always better than "less". However, a high GDP per capita is not synonymous with a high level of individual wealth as GDP also includes investment and trade flows. Some models, therefore, use a more consumer specific welfare criterion of utility, which is the change in consumption levels for a given set of prices (for a discussion of this, see Nordhaus 1994). In climate change modeling, making the distinction between consumers in developed countries and those in less developed countries reveals important equity issues. Few people deal with the intra-country distribution of cost or additional income resulting from climate change and climate change policy[2] because of the primary focus to-date on international concerns. However, some analysis has been conducted (e.g. in the U.S.) on relative winners and losers in the context of a single country.

C. Interventions/Policies/Tools for Emissions Modification

Addressing GHG emissions as an economic externality is a role for government, however, the approaches used by any one government depend on its economy. There is considerable reluctance to intervene to reduce emissions in any economy, but particularly in poor countries, if economic growth might also be reduced. With this double-edged problem in mind, the interventions or policies available to governments are varied and numerous. They are often broadly defined as market-based methods and non-market (or command and control) methods, between which there is considerable overlap. For example, GHG mitigation can be pursued by subsidizing the acquisition of new technology, (a market-based approach) at the same time as forcing publicly managed sectors of the economy to retire old capital equipment or to close inefficient plants (a non-market approach). An alternative categorization of interventions is persuasion and coercion approaches. Taxes and subsidies fall into the persuasion category, while mandates to reduce and prescribe emission controls are coercive in nature.

A third means of categorizing policy options, as presented by the Intergovernmental Panel on Climate Change (IPCC), is by technologies and economic instruments (see Watson, Zinyowera and Moss, eds. 1996). These include:

1. Technologies: buildings (residential, commercial and institutional), transport, industrial, energy sector, agriculture, forest, solid waste and wastewater disposal
2. Economic Instruments:
    a. National-level: subsidies and subsidy elimination, domestic taxes, tradable permits, revenue recycling and tax substitution
    b. International-level: international taxes and harmonized domestic taxes, tradable quotas, joint implementation, policies to reduce free riding and emission leakage.

The most widely studied policy examples are taxes for top-down models and technology changes for bottom-up models. Taxes and subsidies are designed to induce the behavioral modification of private agents in the economy; for instance, a tax on the use of a particularly high GHG-emitting product will

[2] Another interesting discussion is obtainable in the Human Development Index manual published by UNDP, which explicitly deals with the marginal decline in the utility of income with respect to income. Each additional dollar of income has less utility than the previous dollar; in other words, an additional dollar of income for lower income households has more utility than an additional dollar for higher income households.

make firms reduce their use of the product. If firms can reduce this use in the short run, it is because substitutes exist; in the long run, product use will be reduced in any case due to technical change. Similarly, a tax on a household activity that contributes to emissions will make households reduce their consumption of the good or service at issue. The examples in both cases are voluntary reductions to avoid the higher price paid for the polluting activity. The avoidance of the polluting activity, especially by households, will be conditioned by the price elasticity of demand for that good.

A good rule of thumb in selecting persuasive alternative policies is to make the polluter pay, and it is better to implement this policy earlier in the production and consumption chain. Non-polluters later in the chain should not subsidize pollution and, the earlier the tax is imposed, the greater the ramification for all agents in the economy who are either directly or indirectly contributing to emissions.

An example of this can be found in the transportation sector. It is commonly known that transportation services are high contributors to emissions, yet households are reluctant to reduce their consumption of this good. Poor households, although they also consume transportation services, have considerably less flexibility to curtail their demand for transportation services, meaning that there is a low price elasticity of demand. A consequence of such a low price elasticity is that, in persuasive approach, it is more sensible to avoid taxing transportation services, and instead, to tax intermediate demand for high emitting goods, such as the transport fuels. In the form of a considerably less intrusive tax, fuel taxation will achieve more than service taxation. It could be argued that it is always better to tax the polluting input rather than the activity; however, administrative or implementation issues may lead to taxing some final good or service instead.

In the real world as well as in macroeconomic models, taxes on carbon emissions initially reduce household consumption by creating higher prices. Even a tax on intermediate products (as opposed to the final products that consumers buy) will ripple through the economy ultimately affecting the final consumer. Meanwhile, this negative impact on households from the taxes can be offset, to varying degrees, by technical change in production processes. Such technical change can be energy efficiency improvements that arise from producers' response to new input prices or from specific programs and interventions potentially funded by carbon tax revenues.

More coercive policy approaches include reduction mandates. The Annex I and II signatories to the Kyoto Protocol have effectively agreed to coercive approaches to achieve reduction in emissions, by agreeing to reduce their emission levels in 2012 to their 1990 levels. If countries cannot achieve emission reductions targets by persuasion in their respective countries, they will have to achieve them by enforcing limits. This is one reason that further progress on the Kyoto protocol has been stalled. Several developed countries, notably the U.S. and Canada, have argued that they have important sinks like growing forests into which they can retire emissions or store/sequester carbon. They argue that they will likely not need to apply coercive policies to achieve their target of 1990 levels by the year 2010. European developed countries, which have fewer natural sinks, argue that technological investments and the acquisition of emission permits from transition and poorer countries should be the way to reduce emissions. The merits of one point of view over another is a political matter, but one that points to the reluctance of some countries to adopt coercive measures to reduce emissions.

In their stance over whether to use natural sinks or to adopt more coercive measures, the US and Canada have less developed countries as allies. The less developed countries, or non-Annex I countries, are not called upon to contribute to reductions in GHG gases by the year 2012. However, in the not too distant future, they will be asked to contribute and their requirements will grow as countries, currently under a mandate to reduce, ignore the problem in the short run. Many of the poor countries have natural sinks that allow them to retire emissions. However, they are not in a position to sell this benefit because they are non-Annex I signatories under the Kyoto Protocol. In the future, they may carry the heavy burden to curtail emissions that can only be achieved by enforced mandates.

Furthermore, in deciding on a course of action for GHG mitigation, governments must take into account the possibility of inaction on the part of other governments. Such inaction, or unilateral action on the part of single government, can undermine the efforts of others. This is a classic tragedy of the commons and the most ominous problem faced by all nations in developing joint GHG mitigation policies.

In practice, many policies will require micro-level interventions in the form of fuel switching and efficiency improvements, especially in the energy sector. In the long term, it makes sense to consider the turnover of capital stock to achieve reductions in emissions. The additional cost of acquiring more benign equipment can be negotiated among nations where the incremental costs are higher.

By analyzing the net effect of complex results and inter-relationships, one can determine whether one policy or another is an effective method to achieve reductions in GHG emissions. This necessary analysis leads economists and policy-makers to the value of appropriately structured models. The costs and benefits that are generated by any given model are determined by the structure of the model, which is demonstrated in the subsequent sections where specific models are considered. It follows that the type of model one is likely to use depends on *a priori* assumptions about how to capture the benefits and costs of actions designed to mitigate GHG emissions. However, it may not always be possible to have the best model for studying GHG mitigation policies. Absence of data alone can hinder the development of good models, and consequently, models often do not capture all of the feedback linkages and responses that are part of the GHG mitigation debate.

D. Macroeconomic Impacts of Climate Change and Interventions

Macro-economic impacts of climate change are measured in terms of the traditional macro-economic variables. In general, these include sectoral output levels, imports and exports, consumption, and price level variables. In addition, attention is paid to employment levels and wage rates. Investments on a sectoral basis are also often measured. In traditional macroeconomic models, little attention is paid to specific measures of welfare, other than GDP per capita. The emphasis is traditionally placed on output, where the greater the output, the greater is consumption per capita (which is generally true even though as noted above, output also includes investment and trade flows), assuming that population remains constant. As modeling with large numbers of variables has become more feasible, it has become increasingly possible to incorporate specific and targeted measures of welfare.

When attention turns to macroeconomic impacts of climate change, a relatively new set of models, specifically computable general equilibrium (CGE) models, became available to allow more detailed measures of welfare to be considered in assessing the macro-economic consequences of GHG mitigation. One measure often used in these models is the equivalent variation measure of welfare (EV) (Shoven and Whalley 1992). EV is the change in utility of an identifiable group in the economy before and after a policy change under a fixed and original set of prices. The EV takes on a positive or negative value depending on whether the change increases or decreases the income of a particular group. Since the EV model takes prices as being given prior to the policy change, different policies can be compared directly. This measure often moves in conjunction with other macroeconomic variables, but it can move more slowly and in a different direction depending on the types and timing of macroeconomic impacts. For example, an inter-temporal change in technology that occurs early on, may delay consumer welfare gains into the future. If the EV is taken for an early period as opposed to the entire period of analysis, an economy can have gains in sectoral investments at the expense of consumption, or EV, in the short term. One such example is provided in the China model addressed in Part III. Few models are concerned with the distributional question within an economy, and the distributional question in GHG mitigation is more focused across different countries. This of course does not mean that distribution of costs and benefits is irrelevant; it simply reflects the fact that models capable of capturing intra-economy distributional issues require considerably more data and modeling time to develop.

The more detailed information that is available, the better impacts of policies can be traced and more specific policies can be tested. This is particularly important in GHG mitigation because many instruments affect different parts of the economy. The effect of a tax on one activity can either spread throughout the economy or remain localized. The impact depends on the interconnections known or assumed to exist in the economy and how such interconnections are modeled. General descriptions of CGE and macro-econometric models are given in Part II.

One of the most important issues in the GHG mitigation debate is technical change. On one level, technical change is continually occurring as new investment is made to both replace retiring capital and expand production. On another level, technical change is also spurred by government policies (e.g. emission reduction and/or energy efficiency policies), which by affecting input prices via taxes or subsidies, provide incentives toward or mandate choices of technology. In general, changes in technology tend to reduce the emissions of GHG gases due to their general productivity gains and their possible inclusion of environmental concerns or costs.

Adoption of new technology results from a microeconomic cost-benefit analysis, on the firm and household level, indicating that adoption will improve the bottom line. This decision repeated many times amounts to a major macroeconomic change. The issue is how to capture or model this aggregate technical change at the macroeconomic level in terms of:

- Benefits and costs
- Rate and magnitude of adoption
- Technical and sectoral detail.

A related issue is the degree to which technical change is exogenous and/or endogenous to the model and is able to respond to different macroeconomic assumptions or government polices. How technical change is modeled significantly affects the macroeconomic impacts of different GHG mitigation policies. For example, as noted in some of the case studies in Part III, various approaches lead to greater opportunities for policies that are "win-win" rather than trade-off GHG mitigation with economic growth. Such macroeconomic results often arise from the synergy of a number of macroeconomic model structures, some of which enable greater flexibility in responding to policies such that negative first-round economic impacts can be subsequently mitigated. This leads to the point that policies may be "win-win" in the aggregate, but have differential impacts over time and over different sectors and economic agents (e.g. households, firms) such that not everyone is winning all the time.

In simpler and more aggregate models, macroeconomic impacts are often difficult to understand except in the broadest terms, hence more detailed models are useful in the macroeconomic analysis of GHG emission reduction policies. In models such as CGE-structured, prices are explicitly modeled so the impacts of relative price changes, resulting from many policies, can be traced. In more traditional macro-econometric models, this is not the case. Some of the overall issues regarding various macroeconomic concerns and impacts are as follows.

<u>GDP and Consumption</u> -- How well an economy does is most often measured in terms of GDP and consumption levels. The higher both are, the better off the citizens are. Yet while closely linked, GDP and consumption differ by investment and trade issues. For example, it is possible to have an outcome where the prices following their adjustment from a policy such as carbon taxes make it advantageous to invest immediately to alleviate the tax burden and to postpone consumption until after the new capital is installed. This may make consumers less well off in the near term but better off in the longer term.

On the consumption side, few models place emphasis on different classes of consumers (perhaps classified according to income) and the distributional consequences of policies. In dynamic models, including income groups means that households can move from one income group into another and have different shares in their utility functions according to whether they are richer or poorer as a result of a given policy or intervention. This situation is difficult to model. Some static models do have several income groups modeled and in the short-run the distributional consequences of carbon taxes is certainly more difficult to bear by poorer households whose demand for energy is less elastic than it is for richer households.

<u>Prices</u> -- There are important price level variables that interest macroeconomic planners, since in macroeconomic models, the overall price level is of critical significance. It determines the country's comparative advantage in the world, thereby affecting exports and imports. World prices are the critical parameter due to their impacts on imports and exports. Depending on how relative prices change on the world market, a country can lose or benefit from global warming and from policies designed to reduce GHG emissions. All prices, therefore, play a role in determining the outcome of policy. Commodity or sectoral prices are the mechanism by which carbon tax policies are implemented, while sectoral prices affect the wage rate and the return on capital.

<u>Labor</u> -- The most common and appropriate assumption about labor in the macro-economy is that it is available at a given and exogenous wage rate. This is basically the Keynesian assumption, which means that as output rises, so does demand for labor. This is why output serves as a proxy measure of welfare for other important macroeconomic variables such as total employment. The theory of labor availability in developing countries is rich and varied but draws heavily on the Harris-Todaro model. In this model, two labor markets are assumed: one in the urban areas where the wage rate is negotiated and one in the rural areas where the labor pool is large and the wage rate is subsistence. Transition from the rural market to the urban market is based on the urban unemployment rate. In this model, an infinite supply of labor is assumed to be available at a fixed urban wage rate because it can draw people in from the rural areas. Based on this view, in macroeconomic models of poor economies, it is common that the wage rate is fixed and demand for labor is allowed to increase or contract depending on the policy impacts.

<u>Investment</u> -- There are three important investment issues in climate planning. One is the impact to private investments if climate change reduces output. The second issue is how much investment can offset climate change and/or emission reduction policy impacts. The third issues examines where investment funds should come from: public or private as well as national or international.

<u>Taxes</u> -- The use of taxes as an instrument to achieve GHG mitigation raises the issue of how the tax revenues are used or recycled. The question of revenue cycling through the economy is one of the macroeconomic impacts that are generated by policy changes and difficult to trace. One major argument that raises many responses in the macroeconomic impact debate is that mitigation should be achieved at the least cost. Many versions of this have been interpreted and one in particular that stands out is revenue neutrality. If it were possible to shift the burden of mitigation to the polluters while relaxing obligations for non-polluters, reductions could be achieved without large economic costs. Unfortunately, revenue neutrality may not be an easily attainable goal because too many structural changes or economic adjustments may be needed to maintain revenue neutrality. Furthermore, if the revenues are recycled in lump sum form to households, the second round effects on GDP growth and consumption lessen initial reductions in GHG emissions.

An alternative approach is to redesign the tax system to accommodate environmental goals and to eliminate taxes that interfere with the process of wealth acquisition, irrespective of revenue neutrality. Other related issues involve the form of revenue holdings and the method(s) by which they are used to alleviate the cost burden of GHG emission mitigation. For example, one analysis by Cline (1992) argues that governments should retain revenues because of their often-precarious fiscal position, especially among developing countries, and the improvements to their "bottom line" that revenues from mitigation policies can make. Other options are to recycle the revenue via energy efficiency or switching programs that lessen the negative impacts of GHG mitigation policies.

PART II: TYPES OF MACROECONOMIC MODELS FOR CLIMATE PLANNING

A. Overview of Alternative Macroeconomic Models

A.1 Basic Macroeconomic Modeling Issues[3]

Modeling is defined as the use of mathematical constructs to represent reality, in the way we believe that both human beings behave and physical laws prescribe change. The emphasis on the models addressed in this guide go one-step further in that they interrelate physical laws and human behavior via feedback; such as, involving the feedback on the economy of emissions and the consequent human response to that effect.

Models are algebraic representations that link and interrelate variables. Variables fall into two groups: (1) exogenous variables that are changed outside of the model and (2) endogenous variables that change in response to changes in the exogenous variables. These two groups of variables are related by parameters that remain fixed during the modeling exercise. The algebraic representations (or equations) model the best information and assumptions available about the behavior of human beings, and for each endogenous variable there is always one independent algebraic equation. Providing certain other assumptions are met, this equal number of equations and endogenous variables guarantees a unique solution to the model and one that provides insights into the issues under scrutiny.

This report is concerned with the various models that are used to forecast the level of activity in an economy. From these models one can go on to predict the levels of carbon emissions associated with a level of economic activity. The most basic macroeconomic models are aggregate models based on statistical or econometric work, and predict gross domestic product (GDP) and the main components of GDP, which can be used to derive predictions or forecasts based on various policy assumptions. More disaggregated frameworks examine detail at the sectoral level and are often based on an economy's input-output (IO) tables or social accounting matrices (SAM). CGE models are less commonly used for forecasting as such, but allow a more sophisticated analysis of possible policy interventions. In these models, markets are specifically modeled and their interactions analyzed through a set of prices for goods and factors of production (as discussed in the previous section).

Macroeconomic models have been used extensively in economic analysis ever since national income accounts were set up on a reliable and continuous basis, essentially after the Second World War. Such models define relations between macroeconomic aggregates, such as consumption, income, investment, exports, and imports. The variables can be defined in two classes -- those referring to 'real' aggregates, such as those just described; and those referring to 'financial' aggregates, such as the price level, interest rates, and exchange rates.

In macroeconomic modeling, there are linkages between both real and financial variables, so that, for example, interest rates affect total output and changes in aggregate demand impinge on the money markets and prices. In practice, modeling these linkages is a very sophisticated business; the macroeconomic structure of even a simple economy needs hundreds of equations to capture all of the relevant relationships. Such models are mainly used for short term forecasting, i.e. to see how prices, interest rates, exchange rates and output vary over period of one to two years. For most long-term modeling, the macro-models have relatively few financial variables and concentrate on factors that determine growth in the economy. Principally, growth depends on how fast capital is or can be

[3] There are many sources that address basic macroeconomic issues (e.g. Sawyer 1989); therefore, this section is intended only as an overview or refresher for readers.

accumulated, how fast the available labor supply is growing and what technical improvements can be expected in the production processes. A key determinant of these factors is the rate of capital investment.

For forecasting macroeconomic variables and carbon emissions in transition economies, a model is needed that forecasts up to 10 years in the future and encompasses some features of both short and long-term models. Short-term forecasting needs to allow for changes in fiscal policy as government taxation and government investment changes, while long-term projections need to allow for change in the level and type of investment and for different sectoral growth as the economy adapts to a competitive structure.

The first building block of these models is accurate, thorough information and data. All countries publish annual macroeconomic data and a consistent set of data for countries can readily be obtained from the UN from its program of a System of National Accounts launched in 1968. In addition to macroeconomic data, data on GHG emissions and climate change impacts must also be obtained. Although such data is often less available, some general physical relationships are known and can be cautiously applied. For example, GHG emissions from various economic activities can be developed from bottom-up detailed energy sector data, such as energy balances. On another level, a rise in temperature leads to greater evaporation and reduction in water available to crops. The consequences of less water for crops are also well established for many regions in the world, and a prediction can be made of the reduced yield that results from a decline in water.

The data needed to build macroeconomic models includes a time series of aggregate output, consumption and trade variables. There is information available from other sources including input-output (IO) tables, but these are not produced often enough to qualify as time series data, and are one reason that macro-econometric models are usually highly aggregated. In addition, consumer surveys at the national level and the social accounting matrix (SAM), if it is available, yields important information concerning the earning, saving and buying of agents in the economy. A SAM is an enhanced IO table in that it shows how revenues earned on the production side of the economy flow into the hands of agents in the economy. A typical set of agents includes owners of firms, households, a representative government and foreign buyers and sellers.

A second building block is accurate assumptions about how the economy works and how it responds to the behavior of agents and climate change scenarios. A good way to classify models is according to the types of structural assumptions that are embedded in the models and the types of data that are needed to construct them. Below, models are separated into computable general equilibrium (CGE) and macro-econometric models. CGE models are further divided into static and dynamic models; for example, in the case of dynamic models, investment strategies need to reflect the way stakeholder agents behave. Comparing the Tellus U.S. model with the Harvard China Project model of China (both discussed in Part III), the Tellus model uses more technical or specific investment functions for power generation to acquire new equipment that operators of energy generating utilities might use. The Harvard China uses more neo-classical and aggregate investment function to determine investment. The Tellus approach leads to greater reductions in GHG emissions than the alternative specification, with the outstanding issue being whether this approach better captures how capital investment actually takes place. This issue is part of the general challenge of finding ways to incorporate the results of energy sector specific studies into macroeconomic analyses.

Models that are used currently to simulate macroeconomic impacts of climate change are numerous. A first set is composed of models such Cline (1992) and Nordhaus (1994). These are overview models that perform the unique function of analyzing the most fundamental question of whether any action to reduce GHGs is warranted from a macroeconomic perspective. They perform a cost-benefit analysis over the very long term, comparing the costs of GHG emission reduction with the benefits (or costs avoided) from avoiding the damages from global warming.

Other sets of models accept the need for reducing GHG emissions and, therefore, analyze policy options for GHG emission reductions and determine whether a particular policy choice like a carbon tax is not too damaging to macro-economic goals for the economy. In these sets of models, the issues are of when, where and how to best implement policies, generally presuming the need for reducing GHG emissions and focus on analyzing the least cost means of doing so. These questions are more germane to a single country's choice than the Cline and Nordhaus models.

A second set of models, including MARKAL-MACRO and SGM, focuses on global or regional-levels but can be redesigned to address a particular country's issues regarding macroeconomic impacts of GHGs. These models produce costs figures and welfare impacts of selected GHG mitigation policies, letting policy makers decide which courses of action may be best. A third set of models is national and again focuses on evaluating various GHG emission reduction policies and their macroeconomic impacts. These models include those of China, U.S. and Egypt by various researchers.

The models noted above are inter-temporal. They produce results for future time periods, the lengths of which vary. In the case of Cline and Nordhaus, projections are made 300 plus years into the future. In the case of MARKAL-MACRO and SGM, they look often less than 100 years into the future; and in the case of many national models, projection is less than 20 years into the future.

A fourth set of models is static in nature and used to estimate comparative static results of national short-run GHG mitigation policies. This set includes various models (often CGE) developed for national planning, which are modified with emission coefficients to study short-run effects of GHG mitigation policies. These models can be useful since many of the costs of GHG mitigation policies are borne in the short run. Furthermore, policies such as carbon taxes and their impacts on the economy in the immediate future can be studied in detail. The fixed nature of the model, however, makes it impossible to capture technical change that mitigates policy impacts.

Static models should not be used to prescribe capital stock changes, as they do not yield insight into the best place in the economy to make new capital investments. For instance, if a static model is used to show the cost of a carbon tax is high in terms of GDP lost, it will present the maximum amount of money a policy maker could use to invest in new capital that will achieve the same reductions in GHG as the carbon tax. The static model, however, will not be able to identify the best point of entry for this new investment.

Each of these models uses a general macroeconomic modeling approach that is either macro-econometric or computable general equilibrium (CGE). The strengths and weaknesses of each approach from the GHG mitigation policy-analysis perspective are important to understand. Macro-econometric models are used for short to medium term forecasting of macro-economic variables. These models are extremely effective in doing this and since they are estimated on the basis of a historical trend; they are reliable (assuming no major structural changes in the economy). The difficulty with macro-econometric models is that they contain only rudimentary assumptions about human behavior (e.g. responses to price changes), and are usually not very detailed or, in other words, are quite aggregate because they require a large volume of data. For example, a complete data set over a ten-year span is insufficient to calibrate all but the most aggregate econometric model. If the number of endogenous variables in a macro-econometric model is equal to k, there must be at least k independent equations and since the degrees of freedom must be greater than or equal to 1, there must be at least k+1 years of data. A macro-econometric model with only ten endogenous variables can only represent the most aggregate of macro-economic responses and impacts from GHG policies.

On the other hand, multi-sector CGE models (albeit approximate) can be developed with one year of data together along with plausible assumptions about firm and consumer behavior (e.g. profit and welfare maximizing). Comparing and calibrating their performance against several years of observed data could further refine these models. As a result, CGE modeling for applied macroeconomic analysis is a widely used option for modelers. More refined CGE models can be developed that utilize time series data to econometrically estimate the parameters used by the models.

Linking macro-econometric and CGE models to climate change variables is similar. Changes in aggregate output and in consumption lead to changes in emissions. Similarly, changes in prices cause changes in technology and consumption patterns, which, in turn affect emissions. CGE models are richer in the detail they capture on both the sectoral level and the behavioral side. Some of the models discussed in Part III are rudimentary when it comes to behavioral (price response) assumptions and others are more sophisticated. MARKAL-MACRO and SGM are relatively simple models of human behavior, though MARKAL-MACRO much more simple than SGM. While MARKAL-MACRO contains a significant amount of information on technology choices available on the basis of a cost minimization, problems arises when human response opts for welfare or utility maximization rather than cost-minimization – which leads to different results for the two options. The SGM model is more realistic in its assumption about human behavior, especially as it relates to inter-temporal choices (i.e. contains a welfare maximization criterion), and also contains more than rudimentary information on the technology choices available. The Tellus U.S. and the Harvard China models are more sophisticated about modeling human behavior (i.e. contain an inter-temporal welfare function that is maximized in present value terms), but have less information on technology choices. In static models, the issue of technology choices does not arise, but the costs of behavior modification on the macro-economy does arise and these models can give very precise short-term insights, though these impacts will change in the longer term (and such analysis requires dynamic CGE models).

B. Macro-Econometric Models

Macro-econometric models use information about past trends of the economy to model future change. Change in the future is, in part, determined by the state of the economy as defined by its past performance. Algebraic expressions can prescribe the values of the endogenous variables influencing past performance and future change, when given the values of the exogenous variables. To illustrate this type of model and to facilitate further discussion, the following general model taken from Green (1997) can be examined:

$$Y_t = C_t + I_t + G_t$$

$$C_t = f(Y_t, C_{t-1})$$

$$I_t = f([Y_t - Y_{t-1}], R_t)$$

The first equation requires that annual income (GNP) be spent on consumption (C_t), investment (I_t), and government consumption (G_t). The second equation is a behavioral equation and stipulates that consumption is a function of income (Y_t) and consumption in the past (C_{t-1}). The third equation is also behavioral and requires that investment be determined by changes in income over the past and the current rate of interest (R_t). While in this simple example the exact functional forms are not identified, they are typically linear, though many macro-econometric models have non-linear functions.

The model is fully defined by three exogenous variables, G_t and R_t, Y_{t-1}, three endogenous variables, Y_t, C_t, and R_t and three functional forms. The policy instruments in this model are government consumption and the interest rate. The impact of policy changes on these two variables depends on the parameter estimates that map these impacts into changes in the endogenous variables, and these parameters are determined from historical trends. The subscripts of t and t-1 illustrate that the values of the endogenous variables change over time. It is easy to see that investment in the current time period is affected by the growth in national income over the previous time period. However, the aggregate income in this time period also affects consumption, the aggregate of which can be expressed in per capita terms.

Assuming that the interest rate (R_t) is fixed, the remaining exogenous policy variable is government spending, within which is a choice of both its type and magnitude. A larger and more detailed model might explicitly project sources of government revenues and expenditures. Specifically in the GHG mitigation debate, a source of revenue for some governments can be the sale of emission permits and an expense, the acquisition of new technology under the Annex I agreement of the Kyoto Protocol. The magnitude of spending is limited by macro-economic variables. The amount and type of investment is in turn directly related to the economy's contribution to GHG emissions and the impact of government spending on this GHG contribution. The Green (1997) text expounds further on these more complicated models and is recommended reading.

A problem with these models for the study of GHG emission policies is that often they are not sufficiently detailed to capture the economic and GHG emission impacts of policy options. These models are usually too aggregated to reflect the improved technology, redirected spending and/or changed prices (e.g. due to carbon taxes) resulting from climate planning policy. Their general aggregated nature is partly due to the data intensiveness of these models. The more endogenous variables and the more functional forms used the more information that is required to estimate the parameters of a model. The historical data set for many countries is often only sufficient to build aggregate models. Even in countries that have a long tradition of systematically gathering data, the data are insufficient to build sectorally disaggregated models. Furthermore, macro-econometric models do not model human behavior in the detail that CGE models do; for example, they do not allow consumers to substitute between different goods and services or to alter consumption levels in response to price changes.

On the other hand, one advantage of macro-economic models is that they are dynamic; meaning that they can project macro-economic variables into the future, which can be used as inputs for other models. For example, these models can forecast variables of the macro-economy that relate directly to forecasting GHG emissions. Another useful characteristic of these models is that they generate macroeconomic results that are realistic and can subsequently be used in more bottom-up models like MARKAL. Macro-econometric models are best used in conjunction with more detailed models to develop policy alternatives for GHG mitigation.

In conclusion, while macro-econometric models have not been used much to study the relationships between the macro-economy and climate change, they are amenable to more extensive use in this field. They can be used to generate plausible scenarios of the macro-economic aggregates in the absence of any policy that attempts to reduce GHG emissions. These results can then be used in conjunction with other models like CGE models to estimate the economic consequences of implementing policies designed to alter the pattern of emissions. The econometric models are an independent check on the possible growth of the economy. When the economy is forced to change in response to GHG mitigation policies, these independent results can serve to estimate the cost of the new policies to the economy. There are also many variables that are affected by macroeconomic aggregates, notably population growth and labor supply growth. Even in dynamic CGE models discussed below, these variables are estimated using historical trends and statistically estimated parameters.

C. Computable General Equilibrium (CGE) Models

Computable general equilibrium (CGE) models are another class of macroeconomic models, and fall into the "top-down" category. There are a great variety of these models, many of which have given rise to recent, major developments in the GHG debate. CGE models can easily marry macroeconomic variables traced by policy makers with the variables related to GHG emissions. For example, emissions of GHGs can be directly linked to sectoral production, such as electricity-generation sector output. In addition, these models can capture how firms in different sectors can acquire new, less-polluting technology in response to emissions reduction mandates. They also show the potential changes in sector-specific demand caused by higher prices that are created by emissions taxes or other policies.

The strength of CGE models is that they rely on rational human behavior to generate responses to GHG policy choices. For example, if a tax on emissions is levied at the production level, the price of the product will rise and consumer demand may fall. Product output would then fall correspondingly. Alternatively, a consumption tax can be levied at the household level to reduce the consumption of products whose use generates GHG emissions. An example of this is household transportation service consumption, where the importation and purchase of automobiles is the taxed commodity. If the economy does not produce automobiles, such a tax can be beneficial by raising the demand for communal transportation services. This in turn raises the demand for other goods and services and the net GHG emissions can be computed directly. The important point is that these types of typical micro-economic policies can be simulated in CGE models, revealing macroeconomic impacts and their consequences on GHG emissions in the economy.

CGE models specifically analyze demand and supply in each relevant sector. The simplest way to think of them is to divide variables into endogenous and exogenous categories, and to make all prices (or most of them) endogenous. Exogenous variables in the model include initial endowments (such as ownership of land, capital assets and labor), foreign income and world prices. For each market the modeler specifies the demand and supply of a specific good or service; hence, if there are N markets, the modeler will specify 2xN equations of the form:

$$D_i = D_i(p_1, p_2, p_3..p_N; Z_1, Z_2, Z_3..Z_M): i = 1,2,3,....N$$

$$S_i = S_i(p_1, p_2, p_3..p_N; Z_1, Z_2, Z_3..Z_M): i = 1,2,3,.....N$$

"D" represents the market demand, and "S", the supply. Prices are demarcated by "p" (1,2,3) and exogenous variables represented by "Z" (1,2,3,etc). Not all the exogenous variables appear in each equation, but the general representation does allow for that. The normal assumption in the CGE models is that the prices are set so that supply equals demand, as shown in this equation:

$S_i = D_i$ *for all markets 1.2....N.*

This assumption allows the modeler to solve the equation for prices, recognizing that the model's markets are not independent. The value of aggregate demand of all markets must equal the value of aggregate supply, by the way in which demand and supply are defined. This is known in economics as Walras Law, and its implication is that not all prices can be determined in a CGE model -- only relative prices are given. To resolve this constraint, the full set of prices can be determined by selecting one of the prices on the basis of the current level of activity.

One way to explain CGE models is to examine the structure of a simple one. In this example, there are 'i' production sectors, and a single representative household. Each sector is composed of small identical firms, which are profit maximizing, meaning that in the short run their only decision is how many workers to hire. The production function of the firm can be represented, in its simplest form with only two inputs as follows:

$$X_i = f(L_i, K_i),$$

in which, X is physical sectoral output, L is physical labor input, and K is physical capital input.

Labor demand is obtained by equating the cost of labor to its contribution to the value of the output. In the following equation, this condition is shown as flowing from a production function that embodies constant returns to scale and allows for a large response to price changes:

$$W*L_i = \alpha_i * P_i*X_i$$

In this equation, W is the wage rate and P is the price of sectoral output.

Profits (Π) can be shown as the difference between the market value of the product (P*X) and the wages paid (W*L):

$$\Pi_i = P_i*X_i - W*L_i$$

Further, one can designate households (Y) as the recipients of all wage and profit revenues:

$$Y = W * \Sigma_i L_i + \Sigma_i \Pi_i$$

Demand (C) for the product is specified by a demand function that is derived from maximizing a utility function (β) of the household:

$$C_i = \beta_i*Y / P_i$$

The markets clear when physical sectoral output (X) matches demand/consumption (C):

$$X_i = C_i$$

And the sum of each sector's labor equals aggregate labor (L):

$$\Sigma_i L_i = L$$

The above equations constitute a simple CGE model. It has 5 * i + 2 endogenous sector-specific variables, thus has 5* i + 2 equations to represent: output (X_I), labor demand (L_I), profits (Π_I), household consumption (C_I), market clearing prices (P_I), household income (Y), and wage rate (W). The parameters of the models are: L, total labor available; K_i, sectoral capital stock which is fixed in the short run; α_i, the parameters of the production or supply function; and β_i, utility or the parameters of the demand equations.

Based on this approach, many complexities can be added. More sophisticated models include more detailed production functions, which have many more inputs such as energy and other intermediate goods. Furthermore, these functions have more defining parameters that enable substitution between specific inputs (such as labor and capital or energy and capital), thereby modeling more complex technical change. Constant elasticity of substitution (CES) production functions are often used where the difficulty or constraints to switching between labor, capital and other inputs such as energy, can be adjusted by using different elasticities. Such elasticities would be based on different assumptions about the ease and rate of technical change and on the time frame of analysis. Furthermore, the degree or difficulty of substitution can be altered to test the economy's sensitivity to different rates of adjustment.

At the utility function level, a household may first decide on the amount of time to allocate to leisure and work on the whole. Having made this decision, a household may next address the amount of time to allocate to different work and leisure activities, such as work on the family farm or in the wider economy. Having allocated time to household work, household revenue is determined, and then apportioned between consumption of market purchased goods and investment (e.g., investment in the family farm to yield higher food output). This example illustrates that any additional function that adds to the CGE model's sophistication can usually be incorporated into the structure of the model.

There are many types of possible enhancements to these CGE models. For instance, they can incorporate multiple households and trade in the market. The households are defined according to their ability to save, expenditure patterns and sources of income. Trade agents in the economy include foreign buyers and sellers, and different levels of governments. The sector-specific breakdown of these variables and their impacts is often very precise. In other cases, nested production and utility functions are added. In production functions, it can be assumed that firms can substitute among various energy types at the intermediate level.

Large, disaggregated CGE models with many sectors can analyze highly targeted policies for GHG mitigation. It is important to note, however, that any increase in sophistication brings an increase in the number of equations required and in the calibration programming required. There comes a point where additional model detail may not be justifiable given the incremental gains in macro-economic insight versus the incremental difficulty of calibrating the model.

Today there are highly effective software programs that solve large non-linear systems of equations, and help overcome the increase in programming complexity that results from increasing the model's sophistication. One such program is the Generalized Algebraic Modeling System (GAMS). An abbreviated or demonstration version of GAMS, that is sufficient for basic model work, is available from the GAMS Development Corporation for a small cost (see www.gams.com). GAMS can be simulated by a spreadsheet (in Microsoft Excel, etc.), though the models that can be solved in this manner are usually quite simple. More complex representations of reality do not require proportionally more information, but do require proportionally more equations, which can lead to a large effort in calibration.

One of the useful aspects of CGE modeling is that the parameters of the model can be calibrated from a data set for one year. A dynamic CGE model where sectoral capital stock changes over time, requires relatively little additional data to calibrate; however, it requires investment behavior assumptions to introduce additional functional forms that make the model inter-temporal. Such investment behavior is modeled by a number of factors, such as the discount rate, the investment time horizon and the estimated level of mobile capital that can flow between sectors with the highest returns. The practicality of a dynamic CGE model can be verified by its ability to track years' worth of data once it has been calibrated. This point is somewhat controversial and many analysts call for more rigorous statistical estimation of the parameters of CGE models, an area in which macro-econometric analysis can play a useful role (such as the work on China presented in Part III below).

It is important to note the distinction between statistical estimation and calibration of model parameters. Calibration as opposed to statistical estimation is often the only alternative available because only one or a few years of consistent data exist, which is insufficient for statistical analyses. However, even if large data sets exist as for the US, the preferred approach today is often the calibration of CGE models given the mounting experience that calibration is sufficiently realistic for policy impact analysis and is a more simple process to undertake.

The move from static to dynamic CGE modeling and the accompanying calibration is generally not difficult. What is more difficult is to determine the equations that realistically represent how inter-temporal choices are made. Modelers must address question of capital mobility; for example, in a dynamic situation does one always allocate new capital to sectors with the highest return? What sort of lag is involved in moving capital across sectors? Household concerns are also considered, such as whether an increase in wealth also raises the household's savings rate. Each of these questions requires a specific functional form, which is complicated by the many competing views of these issues. For example, many would argue that once capital is installed in a sector, it is unmovable. Others dispute this point and still others argue that it depends on the level of sector disaggregation. These questions still arise in the Harvard China example, where the model is structured such that, even at a 40-sector level of aggregation, capital reallocation across sectors is feasible.

The main additional aspect of dynamic models is their ability to track optimal sectoral capital renewal and increments and the technical change that is embedded in such new capital. In this way, they can be used to test policies that achieve GHG emission reductions, which are often via technical change over time. In effective climate change planning analysis, many of the models are dynamic in nature and have varying time horizons. There is a practical trade-off, however, between the length of time covered by the model and the realistic level of sector-specific detail that can be included. Greater detail over a long period of time results in an extremely complex model, whose development is prolonged to avoid potential errors or inaccuracies in the detailed simulations.

Dynamic models also raise new issues; the most important is the question of selecting a discount rate for valuing future benefits and costs. Even a low positive discount rate reduces the value of future benefits and costs to almost nothing after 50 years. A 1% discount rate after 50 years reduces the value of $1.00 to $0.60 and a 5% discount rate after 50 years reduces the value of $1.00 to $0.09. Fifty years, though it is far in terms of single human life, is short in terms of measuring the benefits accrued of GHG mitigation undertaken today. Many models test the results against different discount rates and find that policies designed to reduce GHGs are sensitive to the discount rate.

Generally, CGE models consider GHG emissions at the production level such that emissions are an output of each sector, and are the dominant source of emissions. Technical change yields reductions in emissions at the output level, but with the inclusion of the additional cost of buying the technology. The consumption side of emissions, i.e. those emissions that are generated at the household level, is therefore often modeled in less detail. Nevertheless, households do adjust their consumption patterns in response to price changes, which reflect the embedded costs of emission reduction policies.

CGE models are becoming increasingly popular for policy analysis partly because they require relatively less data than their econometric counterparts. What they lack in data, the models make up in assumptions, which is precisely their strength. Many of the assumptions are about human behavior and assume rational behavior, meaning that firms and households adjust to policies in ways that continue to maximize profit or welfare. For example, if a tax on emissions is levied at the production level, the price of the product increases and household demand for that product falls. Households adjust their welfare by reducing their consumption of one product and increasing their consumption of other products. Meanwhile, increases in prices lead to reductions in output and correspondingly to reductions in labor demand and household income. After all of these adjustments, one can observe the net macroeconomic impacts of policy choices.

A typical question that dynamic CGE models address concerns the period and the extent to which consumers are penalized due to investment paths that reduce GHG emissions by some percentage within a given period (e.g. 10% reduction over the next 25 years). For example, in the Harvard China model, there is a 5-year initial reduction in consumption as a result of investing to reduce GHG emissions. There is then the issue of whether current consumers accept the penalty, even if consumers are better off in the future.

To summarize CGE modeling, representative issues for the basic assumptions, critical exogenous variables, and critical endogenous variables to these models are as follows.

- Basic Assumptions:

  Endogenous and exogenous variables
  - Endogenous means the variable is determined by the model and can fluctuate
  - Exogenous means the variable is fixed outside of the model

  Small open economy:
  - The country is a price taker in the world markets
  - Open economy contains imports and exports
  - Often fixed trade balance with endogenous exchange rate for developing country

  Standard economic or basic rational behavioral assumptions for market economy
  - Households maximize utility
  - Firms maximize profits

  Substitution exists between goods in response to price changes based on exogenously determined substitution elasticities - usually imperfect substitution (i.e. not easily substituted). Important examples are: labor and capital; imports and domestic products.

  Labor Market Conditions
  - "Neoclassical closure": all markets clear including labor market (i.e. full employment with endogenous wage rate) [standard in developing country context]
  - "Keynesian closure": labor market does not clear (i.e. allows for unemployment and exogenous wage rate) [more relevant to developing countries]

  Static versus dynamic CGE
  - Static means mostly fixed capital stock (only limited changes in technology and no major investment decisions), used for short-term analysis
  - Dynamic means that capital stock can change, used for medium- and long-term analysis

- Critical Exogenous Variables (i.e. determined outside the model)

  Wage rate fixed (Keynesian Closure, with variable employment level)

  Substitution elasticity parameters:
  - Substitution among commodities in final consumption
  - Substitution between capital and labour
  - Fixed coefficients in intermediate inputs (usually)
  - Substitution between domestic products and imports
  - Substitution between producing for exports and for domestic consumption

  Trade balance fixed (with variable exchange rate)

  Foreign savings (development assistance, private investment)

  Fiscal instruments (indirect taxes, subsidies, and parameters of the production function)

  Technical structure of the economy (initially fixed input-output table; dynamic models allow subsequent technical change based on mix of endogenous and exogenous factors; exogenous factors can be rates of productivity improvements or pre-specified changes in technology)

Investment behavior
- Flexible capital movements between sectors
- Some level of immobile capital in non-market or planned sectors

Discount rates

- Critical Endogenous Variables (i.e. determined internally by the model)

  Exchange rate (due to exogenous trade balance)
  Employment level (due to exogenous wage rate)
  Household income
  Exports, imports (on a sectoral basis)
  Output (on a sectoral basis)
  Prices (on sectoral basis)
  Investment and savings levels (and the resulting cost of capital)
  Technical change in dynamic models (based on investment, relative price changes, cost of capital)

The results of CGE models are sensitive to many of the basic assumptions; therefore, it is be useful to undertake sensitivity analysis with regard to various parameters, such as:

- Closure rule whether it is neo-classical or Keynesian, which pertains to whether wage rate is fixed or full employment is assumed; an exogenous wage rate results in unemployment and limits industrial adjustments in labor use hence often has more negative impacts.
- Single versus households, where multiple households can examine impacts on different income or other classes.
- The degree to which households can easily adjust to price changes and mitigate impacts (embedded in the household's utility functions).
- Level of technology change allowed, affecting whether firms curtail output as a result of increased cost rather than adjust by switching to new inputs.
- Whether exchange rate versus trade balance is exogenous/fixed; an exogenous/fixed trade balance can lead to more exports and more domestic production whereas a fixed exchange rate causes fewer impacts but is less realistic.
- Substitution elasticity assumptions: inelastic versus elastic.

The assumptions about substitution elasticities are particularly important because they determine or reflect the ability of the economy to minimize the cost burden in response to various policies. In short-term analyses, elasticities are set low or are inelastic to demonstrate the difficulties of responding quickly to price changes. In the longer-term, more substitution is possible and elasticities are set higher. For example, some initial values used for short-term analysis are:

- Substitution elasticity between labor and capital of 0.333, making it difficult to switch between labor and capital;
- Substitution between imports and domestic output, 0.333;
- Substitution between producing for domestic consumption versus exports, 0.333.

D. Input-Output Models and Social Accounting Matrices

Input-output (IO) tables or models and social accounting matrices (SAM) are very useful sources of economic information for macroeconomic modeling and analysis. They provide detailed data on resource and input (or intermediate product) allocation in all productive sectors as well as final goods consumption across to consumer market groups (households, government, trade). These models can be used to develop larger macroeconomic models or in conjunction with aggregate macroeconomic models to produce more detailed results. IO and SAM models are able to indicate how changes in demand for final or intermediate goods and services ripple through the economy, capturing primary and many secondary effects.

IO tables model the inputs and outputs of the economy and reflect an average technology employed in each sector. These tables are generally static models that do not have the ability to respond to price fluctuations, new investment or technical change. Dynamic versions can be developed to reflect flows of sectoral capital stock and technical change (i.e. such models function with changing technical coefficients).

A SAM model can be described as an enhanced IO table in that it also illustrates the flow of revenues earned in production into the hands of economic agents. A typical set of agents includes owners of firms, households, a representative government and foreign buyers and sellers. In addition, a SAM may contain information on income distribution.

IO models can forecast changes in production in much greater detail, but they require an aggregate macroeconomic model to provide the basis for changes in final demand and imports. IO models have greater data requirements and less flexibility with respect to macroeconomic policy. For example, in macroeconomic models with a Keynesian structure whereby domestic output is determined by domestic demand, there could be unused resources. Typically, input-output models can not demonstrate this type of unused resources, particularly not as unemployment. The basic structure of an input-output model is as follows:
An input-output matrix, $\mathbf{A}_{t-1}$, will expose the existing technologies for production at the beginning of period t.[4] This NxN matrix has a typical coefficient a_{ij} that represents the resource-input of sector 'i''s output in the production of 1 unit of sector 'j's production. Knowing in advance the technologies available, most countries use this type of matrix to represent the actual, existing production technology employed in the economy.

If the final domestic demand in year **t** is given by the vector **FD(t)**, exports in year **t** given by **E(t)** and imports by **M(t)**, the resulting demand met domestically is given by **F(t)**, where:

$$\mathbf{F(t) = FD(t) + E(t) - M(t)}.$$

Further, by defining total domestic output in year t as **X(t)**, the relationship between total domestic output, final demand and I-O matrix is shown as:

$$\mathbf{X(t) = A_{t-1}X(t) + F(t)} \quad \textit{or} \quad \mathbf{X(t) = [I-A_{t-1}]^{-1}F(t)}.$$

Given the path of **F(t)**, we can determine **X(t)** and thereby the domestic outputs of each of the sectors over time. With this set of sectoral forecasts it is relatively easy to make forecasts of carbon emissions. In practice, an I-O matrix would have to take account of:

- Changes in the coefficients a_{ij} as new investments reflect new technologies, and
- Changes in exports and imports that will change the net domestic final demands.

E. Other Modeling Issues for Developing Countries

Much of the macroeconomic modeling methodology has originated and been refined in developed countries. In addition to on-going, general alternations to the models, the developing country context poses its own set of problems for macro-economic and energy related modeling. In their paper entitled "Epistemological Gaps

[4] Bold letters are used to represent matrices and vectors.

Between Integrated Assessment Models (IAMs) and Developing Countries", Morita, Shukla and Cameron note some of these modeling issues as being:

> "… the extent existing IAMs reflect socioeconomic structures in developing countries; whether it is possible to design IAMs to assess the same policy instruments to developing countries; whether regional characteristics are well represented within IAMs; how realistically IAMs estimate climate change impacts on developing countries; and the extent existing IAMs produce acceptable policy options for both developed and developing nations."

The first issue raised here relates to modeling an economic structure. In developing countries, there is often a large informal market that is not accounted for in official statistics. This is especially true in countries where a large component of the GDP is found in agricultural output. The second issue addresses the suitability of policy instruments that are considerably more difficult to apply in developing countries; one example of which is the carbon tax. The third issue notes that the damage function related to the impacts of global warming is derived from developed countries and is simply adapted to developing countries. In this situation, the economic damage of a policy instrument is overstated, which is caused or merely accompanied by an understatement of social costs. The fourth issue is similar in that the parameter estimates of IAM models are also drawn, without further analysis, from those of rich countries. The last issue raises an inter-temporal welfare question, where Morita, Shukla and Cameron say:

> "… It is argued that the cost of mitigation measures will be felt *now*, whereas the actual damage caused will not be felt until much *later*. The discount rate along with strong currencies in rich countries makes the economic argument of shifting the burden of changing the technical structure to poorer countries."

The solution to this obvious set of problems is to undertake more collaborative work among researchers in poor and rich countries. This might well be achieved by developing an "integrated forum" to facilitate communication. In the description of the case studies in Part III, the reader is urged to bear in mind these arguments

PART III: CASE STUDIES OF MACROECONOMIC MODELING OF CLIMATE PLANNING

This section presents a number of case studies or examples of macroeconomic modeling and analysis of GHG emission reduction policies, offering a range of different methodological approaches and issues, including:

- Second Generation Model (SGM)
- Harvard China Project Dynamic CGE Model
- CGE Model for U.S. Climate Change Policy Analysis
- MARKAL-MACRO
- Static CGE Modeling

A. Second Generation Model (SGM)

The Second Generation Model (SGM), developed by Pacific Northwest National Laboratory (PNNL), is primarily designed to address climate change policy analysis on a regional (i.e. multi-country) or global basis (see Sands et al. 1999). It is a top-down dynamic CGE model and can:

- project baseline carbon emissions over time for a country or group of countries;
- find the least-cost way to meet any particular emissions constraint;
- provide a measure of the carbon price, in dollars per metric ton;
- provide some measure of the overall cost of meeting an emissions target; and
- analyze the impacts of carbon permit trading.

Its primary use has been to examine a wide range of scenarios for estimating the carbon taxes necessary to meet specific carbon emission targets, or alternatively, the carbon emission levels resulting from a specific carbon tax. The model can examine carbon trading and consider non-carbon greenhouse gases.

The SGM can operate for a single region or for all regions simultaneously. In the global form of the model, it can be run assuming that some world prices are exogenously determined or all prices are simultaneously determined by market clearing. The approach in this model is that, in a global model, it makes sense to consider that the price of oil is determined by fiat rather than by market clearing. Changes in consumption, sectoral output, and investment that occur under exogenously changing prices can easily be traced back to the exogenous changes. Not only does this give the user a way to determine if the model behaves 'realistically', it also shows what can happen if decision-makers behave as they are expected to behave.

The global SGM has been developed and refined from the data of seven Annex I and six non-Annex I regions. Energy supply and demand information is obtained from several sources: energy balances for physical quantities and IO tables for values. Overall, the primary data requirements include: input-output tables, energy balances, national income accounts, sectoral investment data, fossil fuel resource data, and electricity supply data.

The model is developed by combining equations for the three activities that define an economy: production, consumption and investment. Agents in the economy are owners of firms, the government and a single representative household.

The sectoral level of detail is presented below. The first column lists the sectors and the second column identifies the sub-sectors. A sub-sector is defined as a production unit that produces a single output such as oil. A sector is defined as a unit that produces an aggregate or more generalized product, such as other agriculture. It is important to understand that, whether one is dealing with a sector or a sub-sector, both produce a single product and have a unique market clearing prices that equates supply and demand. The sectoral detail shown in the table below was designed to capture the carbon producing aspects of the economy. For example, though it is aggregate, the individual components in the "service sector" all release carbon into the atmosphere at approximately the same rate.

The sectoral detail for the 2000 SGM version is as follows:

Other agriculture	
Service sector	
Crude oil production	
Natural gas production	
Coal production	
Products from coal	
[Hydrogen fuel]	
Electricity generation	By oil, gas, coal, biomass, nuclear, hydro, solar/wind
Oil refining	
Distributed gas	
Paper and Pulp	
Chemicals	
Cement	
Primary metals	
Food processing	
Other industry and construction	
Passenger transport	[by transport mode]
Freight transport	[by transport mode]
Grains and oil crops	
Animal products	
Forestry	
Biomass	
Residential building energy services	[HVAC, water heat, other]
Commercial building energy services	[HVAC, lighting, other]

The production sectors are characterized by equations that produce aggregate output and use inputs on the basis of prices. The initial production function is derived from a hybrid input-output table developed from a standard input-output table that is expanded to include energy balance data.

The production functions change over time by assuming producers maximize the present value of the firms' assets. They achieve this by choosing inputs and making new investments based on relative prices and by depreciating existing capital stock that needs to be replaced. The prices are the vehicle through which producers react to policies for reducing GHG emissions. In the SGM2000 model, this translates into an equation that allocates sectoral investment in each time period on the basis of the growth in the labor force, the sectoral investment in previous years and an exogenously calculated expected rate of profit for the sector. In addition, investment is generated by 'capital deepening', an increase in the capital-labor ratio, and is effectively an exogenous technical change variable.

Several forms of the production process can be modeled by the SGM, using either fixed or variable coefficients for the variable inputs. In the variable input version, the coefficients are chosen based on relative prices, and substitution occurs according to a constant elasticity of substitution (CES). For a given time period, the firm maximizes profits.

Even capital is treated as a variable input in this model, and the assumption is made that new capital is more the flexible than old capital. Old capital can be described as in the form of clay or, in other words, is difficult to move and adjust. New capital is like putty; it is malleable and mobile. In operational terms, flexibility of new capital is accomplished by making the elasticity of substitution for old capital smaller than the elasticity of substitution for new capital.

Technical change is an important element of production in the SGM, and allowance is made for both neutral and non-neutral technical change. Neutral technical change is defined as an increase in output leaving all input quantities unchanged, while non-neutral is characterized by whether it is labor or capital saving. Such exogenous changes in the parameters of the production functions – the way the model captures technical change - can vary over time.

This model is able to give insights into the impact of GHG mitigation polices globally or regionally and in some cases nationally (when a region consists of one country such as the U.S. or China). The SGM can be run for regions in increments of five years and up to 2050. Results can be summarized via marginal abatement curves that indicate the cost and amount of carbon mitigation over time for a given carbon tax scenario. The marginal abatement curves for a given year are upward sloping, which means that additional carbon emission reductions are increasingly costly; this is consistent with the findings of other models. The SGM China analysis indicates that the marginal abatement curves are flattening out over time, which reflects technical change over time that mitigates emission reduction costs. In other applications, the model can analyze the impacts of carbon permit trading.

B. Harvard China Project Dynamic CGE Model

The China Project of the Harvard University Committee on the Environment developed a macroeconomic model of China for climate change policy analysis. This project was funded by the U.S. Department of Energy, and the model was developed by Garbaccio, Ho and Jorgenson (GHJ) (see Garbaccio, Ho and Jorgenson 1998). This model is intended to provide insights into the policies and impacts of reducing carbon emissions in China. The importance of a model for China is based on two facts. First, it is a developing economy that is growing; and second, it incorporates about one-quarter of the world's population. The choices that Chinese policy makers settle upon can have a significant impact on global emissions in the future. If China decides to ignore the emissions issue, it forecloses the opportunity of other economies to delay the point at which they must reduce emissions.

The GHJ China model is a dynamic CGE model that treats population growth, capital stock increases, technological improvements, and changing consumption patterns of consumers as exogenous. The annual growth rates for the labor force and productivity are both set at about three percent. There are 29 sectors, of which some are broken into market and planned components, depending on the availability of information.

One important aspect of the model is the ability to substitute capital for energy. This means that the welfare loss resulting from an increase in the price of energy (such as from a carbon tax) can be reduced by technical change from substituting capital for energy. This differs from some other models where energy enters as fixed coefficient and carbon taxes that raise the price of energy impose large welfare losses on consumers. The GHJ China model uses a more neo-classical approach to technical change than that others[5], which introduce technical change based on exogenous, detailed energy supply and use analyses.

[5] Such as the Tellus U.S. model

Another important aspect of this model is its realistic representation of the economy as composed of two different types of producers: those engaged in private production (market economy) and those still engaged in government-sponsored enterprises (planned economy). This is accomplished by splitting the output in sectors where both types of firms exist. Each output has its own price; the planned portion is sold at the administered prices while the private output is sold at the market price. The same distinction is also made for sectoral investment. Planned sector firms receive new capital from the state. These public investments are immobile, which reduces the rate at which advantageous substitution can occur to reduce the burden of mitigation policies, such a carbon tax. On the private side of the economy, firms invest (or, in the model, private investment is allocated) based on sectoral rates of return and capital is raised in the market.

Under these conditions, the GHJ China model analyzes revenue-neutral carbon taxes and their impacts on the economy. Carbon tax scenarios are developed that achieve GHG emission reductions of 5, 10 and 15 percent from a "business as usual" baseline. The model baseline is for a 40-year period from 1992. Because of China's, and other developing countries', objections to emission targets, percent reductions from baseline scenarios are used in lieu of emission targets based on those such as 1990 levels. Carbon tax scenarios are thus derived by limiting the emissions in the coal and oil sectors, by the levels necessary to reach the prescribed percentage reduction from the baseline. To keep government net revenues from changing as a result of new or increased carbon taxes, key indirect, sectoral taxes are reduced by an endogenously determined amount.

The sectoral production functions of this model require the input of capital, labor, energy and land. Furthermore, sectoral prices change in response to (carbon) taxes, which consequently raise the price of energy and cause a shift towards inputs other than energy. Those sectors using more energy, directly and indirectly, are more strongly affected and have correspondingly higher price increases. Allowing for oil imports, as an alternative to domestically produced oil, mitigates an oil price increase. As other taxes on firms decline because of the revenue neutrality assumption, investment in capital raises output. In turn, this increase in output requires more energy, which is subject to the carbon tax. Despite an initial decline in household income, increased output yields increases in consumption, and everyone is better off over time.

These results indicate a "win-win" scenario for carbon taxes. Though other carbon tax analyses have not found such positive results in general, this outcome for China is primarily due to a number of ways in which the Chinese economy is thought to behave, which are incorporated in the model. One behavior is, as described above, the shift from consumption to investment as a result of carbon taxes. This shift is a function of how enterprise behavior, revenue neutrality, private saving rates and other factors are modeled, which in turn reflect characteristics of the Chinese economy such as low existing taxes on labor. Another reason is the assumption that the labor supply is inelastic, meaning that the fall in real wages resulting from higher prices due to carbon taxes does not effect the number of hours worked. This assumption is considered appropriate for China, while understanding that an elastic labor supply could change the overall results. In addition, the model's disaggregated structure, with 29 sectors, allows for more substitution possibilities that can lessen carbon tax impacts. Including some planned segments of the economy, rather than leaving market forces in full control also affects the model's results. At the same time, the model accounts for the fact that carbon taxes reduce subsidies and improve economic efficiency.

In this analysis, GHG emission reductions can co-exist along with positive economic development plans; however, clearly the structure and workings of the current and future economy, and how these are modeled, affect the findings.

C. CGE Model for U.S. Climate Change Policy Analysis

Given that models are used to inform the policy debate on GHG reductions, a team at the Tellus Institute undertook a study for the U.S. Environmental Protection Agency to examine how the results and responses of models are dependent on the assumptions that go into their construction. The resulting paper, "A Pragmatic CGE Model for Assessing the Influence of Model Structure and Assumptions in Climate Change Policy Analysis" (see Bernow et al. 1998), uses the CGE model framework to examine industrial energy use in the United States. "Structural alterations" to the CGE model within this framework include the following:

- "Combining the CGE model with an engineering-econometric energy demand" - Neo-classical production functions are replaced with engineering production functions, which are believed to better represent future industrial production and its energy intensity.

- "Treating energy efficiency improvements as capital augmenting and thereby enhancing the productive capacity of the economy" - This is an important issue since it follows that policies designed to mitigate GHG emissions can also enhance the productive capacity of the economy. This is a classic case of a 'win-win' scenario.

- "Allowing for government activity to play a productive role in the economy" - The rational here is that government expenditure can be used to alter significantly the emission trajectory of the economy over time.

These three improvements represent increased coordination between macroeconomic and energy sector/use models by incorporating more detailed energy use and sector information, while at the same time preserving the macroeconomic analytical abilities and sectoral disaggregation common to CGE models.

Unlike traditional CGE models that assume constant returns to scale, this study uses engineering production functions to introduce increasing returns to scale as a source of GHG emission reductions. In the short run, firms can take advantage of increasing returns to scale. In a dynamic framework, this is reasonable even from a neo-classical perspective for short time periods into the future. This process repeats itself over time providing opportunities to the economy to raise output by more than an amount proportional to the inputs and hence, on a unit basis, to reduce its emissions per dollar of value created.

The technical change in industrial sectors is developed exogenously to this CGE model, and is based on an engineering-econometric energy demand model that estimates the potential for cost-effective energy savings. This approach has been considered superior to endogenously determined, technical change because of the difficulties of creating a workable model that still preserves technical details.

This study analyzes two alternative policy scenarios. The first involves creating industrial energy efficiency standards that require firms to accelerate the rate of acquiring new, energy efficient capital. The second policy considers a revenue-neutral carbon tax of $100 per ton of carbon on fossil fuels, where the revenue is recycled partly as an investment tax credit for energy efficiency investments and partly as a labor income tax reduction. The results of a 21-sector economy modeled with this policy indicated that GDP increases at the same time as reductions in carbon emissions occur.

This model approach is a useful contribution to the ongoing effort to better represent changes in technology, in response to GHG mitigation policies, in macroeconomic models. This study provides a good discussion of the appropriateness of these model refinements, which are contrary to the standard neo-classical assumptions. The approach attempts to better address technical change with regard to future energy intensities of different sectors.

D. MARKAL-MACRO Model

MARKAL-MACRO is an economy-energy model, which includes macroeconomic coverage that evolved from the bottom-up energy sector model, MARKAL. This evolution was primarily motivated by the interest in making the demand for energy and other goods and services endogenous to the model, thereby allowing for price and other economic feedback to national policies, such as those related to climate change. MARKAL-MACRO has been used for national analyses in both developed and developing countries as well as for analyses of international cooperation (e.g. joint implementation).

The energy sector detail is handled by the MARKAL component, which is a program for allocating investment funds on a minimum cost basis to capital projects in the energy sector, to meet predetermined goals such as energy demand forecasts and GHG emission targets. It is a linear programming model that contains a large database of technologies available for meeting energy requirements. It is a 'bottom-up' model that takes energy demand scenarios over a planning horizon as given, and finds the best combination of technology to meet energy requirements at least cost. Its strength has been in the range of choice that can be built into its database to determine a more environmentally benign energy growth path.

At the same time as MARKAL was developed, "top-down' models were developed that contained considerably less information on technology alternatives, but had better macroeconomic analysis features to justify investment in all sectors, including energy, while satisfying environmental objectives. A distinguishing feature of the 'top-down' model is that prices regulate choices in the economy. Variations of MARKAL were developed to expand its capabilities, for example, "Extended MARKAL" (Kanudia and Loulou 1999) incorporated price elasticities into energy demand functions, to better capture an economy's response to climate change policies. This however, this is only a partial equilibrium model as it lacks broader feedback from the economy. MARKAL-MACRO introduced a macroeconomic model component that provides more extensive coverage of the economic impacts and feedback from climate change policies. This key component is a CGE model that captures feedback between energy system decisions and macroeconomic variables such as investment, employment and national income. Furthermore, the model goal becomes welfare or aggregate utility maximization rather than cost minimization.

Both 'bottom-up' and 'top-down' models are dynamic because the decisions made in one time period have repercussions on decisions made in subsequent time periods. Dynamic models also inter-relate three factors. First is the anticipated level of economic development that can or will be achieved in an economy. Second is the level of energy demand by type of energy that meets the needs of the society. Third is the type and level of the supply system that is put into place to meet the energy needs. The feature that distinguishes top-down from bottom-up models is the inter-relationship among these three factors.

MARKAL programs the third factor very well. The MARKAL-MACRO version that was applied to the U.S. economy (Manne and Wene, February 1992) can equate energy supply and demand at the least cost, from among 15 supply technologies, 30 demand technologies and 10 different fuel types. The level of energy demand, by form of energy, has traditionally been treated as an exogenous variable in MARKAL. There has always been a short-term price adjustment to equate demand and supply, but there was no endogenous process whereby prices influenced the level of economic growth and other macroeconomic factors, and consequently, the level of energy demand. In MARKAL-MACRO, energy demand, as well as macroeconomic factors, is endogenous.

As noted above, MARKAL-MACRO reflects a process of incorporating price responsiveness and macroeconomic linkages to the MARKAL energy sector model. One variant of MARKAL applied to India (Kanudia and Shukla 1998) introduced demand functions with price elasticities for energy demand that are greater than zero. In effect, a standard MARKAL had defacto price elasticities at a demand of zero since the demand was determined outside of the programming model. In this model for India, energy prices are determined by the requirement to meet a GHG emission constraint, and the resulting prices are a function of the price elasticities (and their impacts on energy demand) and of the additional cost of meeting the constraint. This MARKAL model variant generated a reduction of 4 to 20 percent of end-use demand once price elasticities were incorporated, which is a significant impact on the results. In this model that includes energy price feedback, the investment choices are still determined without recourse to prices; thus, it is not a fully integrated macro-economic model. Furthermore, there is neither provision for cross-price elasticities to impact energy demand, nor for broader supply and demand responses arising in other sectors.

In MARKAL-MACRO, a CGE macroeconomic model drives energy demands as follows. First, energy demands are determined in response to economic growth and to conservation and substitution measures. Conservation measures are autonomous, react to price changes, and are incorporated via the autonomous energy efficiency improvement (AEEI) factor, as is the case in 'top-down' models. The AEEI is in effect an exogenously determined trending multiplier function that increases output over time in a production function. The argument for this is that any capital turn-over and deepening leads to a gain in efficiency, hence a reduction in energy inputs or a reduction in emissions, in turn lowering energy investments required to mitigate emissions and achieve any given level of output. This approach to improvements in efficiency is controversial, and it does not distinguish MARKAL-MACRO from other models because the AEEI is part of most dynamic models. The distinction between models often concerns the rate of growth of the AEEI.

In MARKAL-MACRO, the production function is now a nested or dual-hierarchy CES function. Capital and labor are combined to form a value-added input, which is combined with an energy aggregate at a higher level. This approach allows energy to be substituted for by increases in added value. As a result, when energy becomes expensive, as it is expected to be under mandates to reduce CO^2 emissions, less energy can be used and replaced by increased capital and labor. There are also benefits realized when this new capital is more efficient, producing more output per unit of capital. Inter-fuel substitution may also occur in the MARKAL portion of the program, the mix of which is determined by cost minimization given the available technology choices.

In MARKAL-MACRO (as well as later MARKAL variants), the terminal condition allows for a more realistic choice mechanism over the planning horizon. MARKAL-MACRO uses the assumption that in the post-planning period, growth in demand will continue exponentially as it did over the planning period.

An application of MARKAL-MACRO to the U.S. economy (Manne and Wene, February 1992) produced significantly different results in projected GHG emissions, when compared to using MARKAL with exogenous macroeconomic forecasts. This application of MARKAL-MACRO had a strong, aggregate macroeconomic model component that limited some of the linkages between the macroeconomic and energy sector modeling. It also constrained the complexity of the functional forms that are used for reflecting production and other economic activities and interactions in the model. Such constraints, in turn, reduce the types of economic responses to policy measures that can be analyzed (such as changes in sector activity, investment and employment as well as substitution among inputs). Furthermore, the resulting, simplistic formulas less accurately capture human behavior. The general approach of MARKAL-MACRO, however, can be applied with a more detailed macroeconomic component that would better capture macroeconomic behavior and policy responses, and generate more factors endogenously.

A comparison of MARKAL-MACRO and MARKAL alone in the Netherlands (noted in Kanudia and Loulou 1999), found an approximate 20 percent greater reduction of GHG emissions under MARKAL-MACRO. These outcomes indicate the importance of including feedback between energy sector and macroeconomic modeling regarding prices and changing economic activity.

In comparison with other models such as SGM and GHJ China, the macroeconomic MACRO model component is less integrated with the energy sector since much of its detail is handled by the MARKAL component. Hence, even with more detailed MACRO implementation, the modeling of some of the economic responses to climate change policies might be constrained by the level and types of linkages between MACRO and MARKAL. It is also important to clearly separate what energy related issues are captured in MACRO versus MARKAL so that there is no 'double counting'; for example, to avoid overlap between the AEEI in MACRO with conservation or energy efficiency measures in MARKAL.

In analyzing climate change policies, MARKAL-MACRO can capture GHG emission reductions from energy system changes, energy price responses and changes in macroeconomic variables. The impacts on macroeconomic aggregates from different policies can be estimated if a more detailed form of MACRO is used. Although it contains extensive energy sector detail, the level of detail in the MARKAL macroeconomic model is less than in other models, thereby limiting some of the macroeconomic responses to policies and limiting macroeconomic impact assessment. Through the use and development of models such as MARKAL-MACRO, DICE (Nordhaus, 1994) and SGM, the various structures of the models are beginning to converge. The trend shows these CGE macroeconomic models becoming more disaggregated and integrating more energy sector detail regarding conservation, fuel-switching and technology choice.

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